

1 **Original Article**

2
3 **Use of computational fluid dynamics to compare upper airway pressures and airflow**
4 **resistance in brachycephalic, mesocephalic, and dolichocephalic dogs**

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6 R. Fernández-Parra ^{a, b, c, *}, P. Pey ^{d, e}, L. Ziberstein ^a, M. Malvè ^{f, g, h}

7
8 ^a *Ecole Nationale Vétérinaire d'Alfort, Paris, France, 7 Avenue du General de Gaulle, 94704*
9 *Maisons-Alfort, France*

10 ^b *Department of Small Animal Clinical Science, Western College of Veterinary Medicine,*
11 *University of Saskatchewan, 52 Campus Drive Saskatoon, SK S7N 5B4, Canada*

12 ^c *Institut national de la santé et de la recherche médicale (INSERM), U955, Equipe 03, 51*
13 *avenue du Maréchal de Lattre de Tassigny, 94010 Créteil cedex, France*

14 ^d *Antech Imaging Services, Fountain Valley, CA 92708, USA*

15 ^e *Department of Veterinary Medical Science, University of Bologna, Ozzano dell'Emilia, Italy*

16 ^f *Department of Engineering, Public University of Navarre, Campus Arrosadía s/n, 31006*
17 *Pamplona, Spain*

18 ^g *Aragon Institute of Engineering Research, University of Zaragoza, C/María de Luna s/n,*
19 *50018 Zaragoza, Spain*

20 ^h *Centro de Investigación Biomédica en Red - Bioingeniería, Biomateriales y Nanomedicina,*
21 *CIBER-BBN, C/Poeta Mariano Esquillor s/n, 50018 Zaragoza, Spain*

22
23
24
25
26 *Corresponding author. Tel.: +33 (0) 1 43967349.

27 *E-mail address:* rocio.fernandez@vet-alfort.fr (R. Fernández-Parra).
28

29 **Abstract**

30 Brachycephalic dog breeds are prone to breathing difficulties because of their upper
31 airway anatomy. Several surgical techniques exist to correct anatomical pathologies and
32 common surgical approaches aim to correct functional abnormalities in the nares and/or the
33 soft palate. However, further research is needed to improve clinical outcomes. This study
34 evaluated air pressure and airflow resistance in the upper airways and trachea in nine sedated,
35 sternally recumbent dogs of different skull types (dolichocephalic, $n=3$; mesocephalic, $n=3$;
36 brachycephalic, $n=3$). CT images were acquired from the nostrils to the caudal border of the
37 lungs and geometrical reconstruction of the upper airway and trachea was performed.
38 Analysis of computational fluid dynamics was performed using inspiratory flow adapted to
39 bodyweight for each dog. Flow (L/min) and pressure (cmH₂O) were computed for the entire
40 upper airway and trachea. Resistance (cmH₂O/L/min) was calculated using pressure
41 differences between the nose, larynx, and trachea. In this pilot study, statistical comparisons
42 were not performed.

43

44 Pressure maps, airflow, and resistance were similar in dolichocephalic and
45 mesocephalic breeds. Median pressure difference (3.76 cmH₂O) and resistance (0.154
46 cmH₂O/L/min) between the nose and larynx were numerically higher in brachycephalic dogs
47 than in other breeds (0.45 cmH₂O and 0.016 cmH₂O/L/min, respectively). Median pressure
48 difference (0.205 cmH₂O) and resistance (0.009 cmH₂O/L/min) between the larynx and
49 trachea was numerically similar in all dogs, except for the English bulldog. The methodology
50 used in this preliminary study to quantify airflow characteristics such as pressure and
51 resistance could improve the understanding of brachycephalic obstruction airway syndrome.

52

- 53 *Keywords:* Airway resistance; Brachycephalic dogs; Computational fluid dynamics;
- 54 Computerized tomography images; Pressure

55 **Introduction**

56 The anatomy of the upper airway is highly varied between dogs of different breeds
57 and skull shapes. Dog breeds are classified according to their skull index (the ratio of skull
58 width and length) into three basic types: dolichocephalic, mesocephalic, and brachycephalic
59 (Evans and de Lahunta, 2012). A shorter muzzle carries a higher risk of brachycephalic
60 obstruction airway syndrome (BOAS; Packer et al., 2015). This pathology is characterized by
61 an elongated soft palate, stenotic nares, and/or everted laryngeal saccules. Some
62 brachycephalic dogs can also have narrowed trachea, laryngeal collapse, and/or laryngeal
63 paralysis, resulting in upper airway obstruction and clinical signs of BOAS (Dunié-Méridot et
64 al., 2010).

65
66 Pulmonary function tests are used in human medicine, but their application in
67 veterinary medicine can be challenging (Hoffman, 2007; Balakrishnan and King, 2014).
68 Spirometry or pneumotachography are used clinically in dogs and cats to obtain flow-volume
69 and/or volume-pressure loops, which provides information about airflow rates, volumes over
70 time, and inspiratory and expiratory peak pressures and times (Amis and Kurpershoek, 1986;
71 Hoffman, 2007). This technique can also be used to identify tracheal collapse in dogs (Pardali
72 et al., 2010), but is relatively insensitive to upper airway resistance to air flow. Whole-body
73 barometric plethysmography can be used in unsedated dogs (Bedenice et al., 2006). One
74 study reported that this technique could determine the severity of BOAS and diagnose the
75 condition in French bulldogs with 95-97% sensitivity (Liu et al., 2015); however, it is purely
76 a research technique. In brachycephalic dogs, there is high pressure in the pharyngo-laryngeal
77 region during inspiration because of proximal obstruction to airflow (Amis et al., 1996),
78 causing distortion and collapse of the laryngeal arytenoid cartilages (Koch et al., 2014).

79

80 Advances in radiography, CT (Grand and Bureau, 2011; Stadler et al., 2011),
81 magnetic resonance imaging, and endoscopy (Bernaerts et al., 2010) have contributed to our
82 understanding of the canine upper airway function and anatomy. CT and three-dimensional
83 (3D) internal rendering can accurately indicate the presence and sometimes the cause of
84 upper airway obstruction in dogs (Stadler et al., 2011). It is the imaging modality of choice
85 for stent selection in dogs with tracheal collapse (Williams et al., 2016).

86

87 Computational fluid dynamics (CFD) uses numerical algorithms to analyse flow
88 characteristics in a variety of situations, such as during respiration. CT and CFD in human
89 patients has allowed computation of nasal airflow (Kyun Kim et al., 2013), upper airways
90 (Gemci et al., 2008; Luo and Liu, 2008), stenosis (Brouns et al., 2007; Malvè et al., 2013),
91 and sinonasal lesions (Lindemann et al., 2005). Numerical simulations have also been used to
92 test medical devices and improve their design (Malvè et al., 2012). CFD studies have been
93 performed in bats and rats to aid toxicology investigations (Zhao et al., 2006; Yang et al.
94 2007; Eiting et al., 2014), and airway fluid dynamics and stenting techniques have been
95 reported in rabbits (Malvè et al., 2014; Chaure et al., 2016). CT and CFD techniques have
96 been used in a mesocephalic dog (Labrador) to examine nasal airflow (Craven et al., 2007)
97 and recently to quantify and compare airway resistance in 21 English bulldogs (Hostnik et al.,
98 2017) to study BOAS.

99

100 The aim of this pilot study was to use CT-based CFD modelling to compare airway
101 geometry, airflow, pressure, and resistance in dolichocephalic, mesocephalic, and
102 brachycephalic dog breeds. Our hypothesis was that the computed airflow, pressures, and
103 resistance would be more heterogeneous in brachycephalic breeds than in dolichocephalic or
104 mesocephalic breeds.

105

106 **Materials and methods**

107 *Dogs*

108 Nine adult client-owned dogs presented to the Veterinary Medicine Hospital of Alfort,
109 France were enrolled in this prospective study. All enrolled dogs required sedation for CT
110 examination for reasons unrelated to this study. Respiratory signs were absent during
111 physical examination in any of the dogs. From 135 dogs scheduled for CT over a period of 18
112 months, 12 dogs were recruited for this study after exclusion criteria were applied. Exclusion
113 criteria were as follows: dogs requiring intubation for imaging, presence of respiratory or
114 cardiovascular disease, closed glottis, pulmonary abnormalities, intraluminal tracheal mass,
115 or invagination of the dorsal tracheal membrane, vomiting, hypersalivation, tremors or/and
116 myoclonus. Three of the 12 **initially enrolled** dogs were excluded because abduction of the
117 cordial cord of the larynx was observed during CT reconstruction. Three dolichocephalic
118 dogs (Great Dane, Whippet, and Dachshund), three mesocephalic dogs (Belgian Shepherd,
119 Labrador, and Brittany spaniel), and three brachycephalic dogs (French bulldog, Boxer, and
120 English bulldog) were **finally** included, based on skull index. Median weight of the nine
121 enrolled dogs was 27.4 kg (range, 10.3–78.6 kg). Food, but not water, was withdrawn 12 h
122 prior to CT examination.

123

124 *Ethical approval*

125 All procedures were conducted as part of normal veterinary clinical practice with the
126 owner's consent (Art. R242-48, Ordre National de Vétérinaire) and approval from the Head
127 of the Veterinary Medicine Hospital of Alfort, France (**7th September 2015**).

128

129 *Sedation and multidetector computed tomography (MDCT) protocol*

130 All dogs were sedated IM with a combination of 5 µg/kg dexmedetomidine
131 (Dexdomitor, Orion Pharma), 0.3 mg/kg midazolam (Hypnovel, Hoffmann-La Roche), and
132 0.3 mg/kg butorphanol (Torbugesic, Zoetis). Once sedated, an IV catheter (Delta Med) was
133 aseptically placed in a cephalic vein. IV fluid therapy with crystalloids (Ringer's lactate, B.
134 Braun) was administered at 5 mL/kg/h during the CT procedure. A multiparametric monitor
135 (Vet Care Monitor, B. Braun Vet Care) was used; side-stream capnography in the nares
136 measured respiratory rate and expired CO₂ (mmHg); pulse oximetry provided the pulse rate
137 and arterial oxygen saturation; and body temperature (°C) was measured with a rectal
138 thermometer. Physiological parameters were measured every 5 min. Dogs spontaneously
139 breathed room air and were placed in sternal recumbency with the head elevated and the neck
140 fully extended. Images were acquired from the nostrils to the most caudal border of the lungs
141 (Hostnik et al., 2017). Non-contrast-enhanced MDCT examinations were carried out using a
142 64-detector-row CT system (Brilliance 64; Philips). Images were obtained using a collimation
143 of 64 × 0.9 mm, a matrix of 512 × 512, tube voltage of 120 kV, tube current of 400 mA, and
144 tube rotation time of 50 s. One millimetre thick images were reconstructed using a high-
145 resolution algorithm. At the conclusion of the CT examination, atipamezole (Alzane, 5
146 mg/mL, Zoetis) was administered IM at the same volume as dexmedetomidine. Recovery was
147 supervised until complete.

148

149 *Image analysis*

150 Images were viewed using OsiriX software (v.5.8.2, 64-bit, Pixmeo SARL) with a
151 lung window (window width [WW] 1600; window level [WL] -550). A board-certified
152 radiologist evaluated the images for major abnormalities involving the airways and
153 measurement of the skull index. Images were displayed using a bone window (WW: 1500;
154 WL: 300).

155

156 *Measurement of skull index*

157 The skull index was obtained by dividing the skull width by skull length (skull
158 width/skull length \times 100). The width was taken at the widest interzygomatic distance. The
159 length was taken as the distance between the inion (most prominent projection of the occipital
160 bone, i.e., the external occipital protuberance) and the prosthion (most forward projecting
161 point of the maxillary alveolar process at the midline). A previously reported skull index
162 (Koch et al., 2012) was also calculated using the ratio of the length of the skull to the length
163 of the cerebrum. The length of the cerebrum was defined as the length from the rostral border
164 of the cranial cavity to the inion. The width and length were measured using multiplanar
165 reconstruction CT images (high-resolution algorithm and displayed on the bone window).
166 The results of the skull index measures are summarised in Table 1.

167

168 *Geometrical reconstruction and numerical discretization*

169 The DICOM (Digital Imaging and Communications in Medicine) files derived from
170 the CT scans were imported into the image-based geometry reconstruction software
171 (MIMICS, Materialise Software). A manual reconstruction of the upper airway and trachea
172 geometry was conducted for each dog (Figs. 1 and 2). The air nasal passage was filled with a
173 threshold throughout all contiguous images until the trachea (green colour in Fig. 1, sections
174 1, 2, 3, and 4), generating a 3D solid model. In Fig. 1, the model of the Great Dane is
175 depicted in purple as an example.

176

177 The volume of each model was then subdivided in a CFD mesh consisting of
178 tetrahedral elements in the software package (Ansys IcemCFD, v.16, Ansys). At this stage,
179 the minimum size of all tetrahedral edge lengths was specified to control the number of

180 elements. Near-wall regions required a denser mesh with more elements (Fig. 3) to capture
181 the gross geometry of the small airways. The minimum edge length varied depending on the
182 skull index type, generating computational grids of approximately 20×10^6 elements. A mesh
183 independence analysis was carried out to assess the effect of the computational mesh on the
184 results. The number of elements of the computational mesh was progressively increased, and
185 the pressures at the locations depicted in Fig. 3 were computed and plotted for different mesh
186 densities. Nasal pressure (section 1) seemed independent of the global element number, while
187 the laryngeal and tracheal pressures increased only slightly (in absolute value) with
188 increasing mesh element number (section 2, 3, and 4; Appendix).

189

190 *CFD analysis*

191 The numerical grids from the nine dogs were imported into a simulation software
192 package (ANSYS CFX, v.16, Ansys). The numerical approach used by this software is
193 explained in the software manual (Ansys, 2016). Continuity and Navier-Stokes equations for
194 turbulent flow were used to solve canine airflow for an incompressible and Newtonian steady
195 fluid (Craven et al., 2009) using an air density of 1.185 kg/m^3 and viscosity of 1.83×10^{-5}
196 Pa·s, respectively (Malvè et al., 2013).

197

198 The imposed peak inspiratory flow was as previously published for dolichocephalic
199 and mesocephalic breeds (1.125 L/kg/min ; Rozanski et al., 1994) and brachycephalic dogs
200 (0.83 L/kg/min ; Bernaerts et al., 2010). These values were first adapted to individual
201 bodyweight by computing different values for each dog and then applied at the nasal aperture
202 representing the model inlet and at the distal tracheal section (model outlet; Fig. 3).

203

204 *Resistance evaluation*

205 The upper airway resistance was evaluated using pressure computed at different
206 locations of each skull model (Fig. 3). Equivalent locations were used for each skull. The
207 upper airway resistance was calculated as follows:

$$208 \quad \text{Resistance (cmH}_2\text{O/L/min)} = \Delta p \text{ (cmH}_2\text{O)/flow (L/min)}$$

209 where Δp is the pressure difference between two anatomical locations and the flow is
210 calculated as the mean airflow passing through these sections.

211

212 Additional details are as follows: section 1, between the nasal entrance and the
213 proximal larynx, which was taken at 1 cm inside the nasal cavity; sections 2 and 3, between
214 the proximal and distal larynx, which was taken 2 cm above and below the larynx,
215 respectively; and section 4, between the larynx and trachea, which was taken 10 cm from the
216 larynx, inside the trachea. The location of sections 2, 3, and 4 varied slightly and in
217 proportion to the tracheal length for each dog. Pressure difference (Δp) and resistance
218 between the nose and larynx were computed using sections 1 and 2 (Fig. 3), while Δp and
219 resistance between the larynx and trachea were computed using sections 2 and 3. Section 4
220 was used only for the mesh sensitivity analysis described previously.

221

222 **Results**

223 The airflow (Δp) and resistance between the nose and larynx and between the larynx
224 and trachea for each dog breed are summarised in Tables 2 and 3, respectively. The flow
225 inside the upper airway and trachea is depicted in Fig. 4, using streamlines that represented
226 the spatial direction of the flow coloured with the velocity intensity (0-20 m/s).

227

228 The upper airway and trachea in dolichocephalic and mesocephalic dogs generated
229 similar velocity and pressure maps. The flow velocity inside the sinus was low (<1 m/s;

230 depicted in dark blue in Fig. 4 and indicated by blue arrows). The flow velocity in nasal
231 cavities and the ethmoidal- and maxillo-turbinate regions ranged from 0 to 11.11 m/s. In
232 contrast, numerically higher flow velocity was observed for the Boxer and English bulldog in
233 the hard palate at the maxillo-turbinate region and at the larynx, respectively (20 m/s,
234 depicted in red and indicated by red arrows, Figs. 4g and 4i).

235

236 The pressure map inside the upper airway and trachea is shown in Fig. 5 (legend
237 values range from -10 to 10 cmH₂O in terms of the atmospheric pressure). For each
238 dolichocephalic and mesocephalic dog, the pressure contours showed an almost uniform
239 pressure (2-4 cmH₂O) distribution in the upper airway (Fig. 5, upper and median panel). Only
240 the Whippet (Fig. 5b) demonstrated some local pressure increase in the nares (depicted in
241 yellow and indicated by a yellow arrow; Fig. 5b). In contrast, the brachycephalic dogs had
242 highly nonhomogeneous pressure distributions (2-10 cmH₂O). In the French bulldog, a
243 pressure difference of 2-4 cmH₂O was observed in the section just proximal to the soft palate
244 (Fig. 5h, lower panel, depicted in yellow and indicated by a yellow arrow).

245

246 In the English bulldog, Δp of approximately 14 cmH₂O (from light green to dark blue)
247 was observed (Figs. 5i and 6a, blue and green arrows; dark blue is due to sudden low pressure
248 caused by the stenosis upstream). This was attributed to high velocity flow (20 m/s)
249 immediately caudally to the stenosis (red colour in Fig. 4i and 6b, indicated by the red
250 arrow).

251

252 In the Boxer (Fig. 5g), different colours (red, green, and yellow indicated by
253 respectively coloured arrows) represent abrupt pressure changes. Red indicates peak pressure
254 caused by a constriction downstream to the skull, proximal to the larynx. This dog had an

255 abnormal pressure decrease between the nasal cavities and the sinus (10-2 cmH₂O), which
256 was not observed in the other eight dogs (Figs. 5 and 7). This indicates asymmetric left and
257 right nasal cavities and uneven pressure distribution (Fig. 7a) and resistance due to local flow
258 acceleration (Figs. 7a and 7b). There was a local increase in flow velocity in the left nasal
259 cavity (depicted in red, Fig. 7b). The pressure in Fig. 7a has a different threshold to Fig. 5g.
260 This emphasizes the dramatic increase in pressure in the Boxer compared with the other
261 breeds and demonstrates that there were local variations in pressure regions in the skull of
262 this dog.

263

264 Stenotic anatomical regions in brachycephalic breeds caused flow variations (Figs. 6
265 and 7) and, as a consequence, variations in pressure and the resistance (Figs. 8 and 9). In
266 Figs. 8 and 9, respectively, Δp and resistance are plotted and compared between breeds,
267 including data from a close-up view for each group. All dogs exhibited Δp proximal and
268 distal to the larynx (Fig. 8), but this was especially enhanced in the English bulldog (Figs. 5i,
269 8b, and 8b.3). The largest pressure reduction was reflected in computed resistance (Figs. 8
270 and 9b). Resistance to airflow between the nose, larynx, and trachea (Fig. 9) was numerically
271 higher in brachycephalic dogs (Tables 2 and 3). Brachycephalic dogs had numerically higher
272 resistance between the nose and larynx than mesocephalic or dolicocephalic dogs (Figs. 9a
273 and 9a.3).

274

275 **Discussion**

276 This study demonstrates that it is possible to examine pressure and resistance
277 noninvasively in the canine upper airways and trachea for different skull conformations using
278 a CT-based CFD technique that is widely used in humans. There are several reported
279 approaches to determine skull index (Koch et al., 2012). The values obtained in the present

280 studies differ from those previously published (mesocephalic, $n=39$; brachycephalic, $n=52$;
281 Evans and de Lahunta, 2012) and this may be related to the measurement technique, as
282 previous studies used either conventional radiographic films (Regodon et al., 1993), or
283 external measurements with a soft measuring tape (Packer et al. (2015), measuring the
284 muzzle and cranial length. To our knowledge, there are no published studies investigating
285 relationships between the degree of brachycephaly using skull measurements and the severity
286 of clinical signs.

287

288 In this pilot study, different brachycephalic breeds presented a wide degree of
289 variation in computed airflow resistance, despite the lack of respiratory signs. Increased
290 upper airway resistance results in increased respiratory effort, clinically visible as respiratory
291 distress or decreased airflow due to prolonged inspiratory time (Pardali et al., 2010). Stenosis,
292 high pressure and increased airflow resistance were detected in the hard palate at the maxillo-
293 turbinate region of the Boxer and in the larynx of the English bulldog. Furthermore, in the
294 geometric reconstruction, we observed tracheal hypoplasia in the English bulldog, a breed
295 known to be predisposed to tracheal hypoplasia (Coyne and Fingland, 1992). The computed
296 resistance and Δp were extremely high. Brachycephalic breeds can have anatomical
297 differences, potentially predisposing individual dogs to respiratory signs. Packer et al. (2015)
298 concluded that breeding for flatter faces dramatically increases the risk of chronic airway
299 obstruction in dogs and could result in an unintentional pathology which could be detrimental
300 to animal welfare. Our results suggest that although the upper airway anatomy in the dogs we
301 studied was genetically altered, they were able to compensate by breathing through their oral
302 cavity during our examinations, resulting in high respiratory rates and lower tidal volumes,
303 perhaps predisposing to a sedentary lifestyle.

304

305 We believe that simply resecting the nares and a portion of the soft palate does not
306 correct the basic problem in dogs with BOAS. Upper airway resistance and Δp were
307 numerically higher in all brachycephalic breeds in our study, especially in the ethmoidal
308 region, reflecting the findings of Hostnik et al. (2017). The ethmoidal region, especially the
309 edematous mucosa, has been proposed as important in airway disease of brachycephalic
310 dogs; however currently, the only surgical correction available is nasal turbinectomy
311 (Oechtering et al., 2016). Our findings document previously unreported (Lorenzi et al., 2009)
312 anatomical regions that could be pathologically altered in brachycephalic dogs, which are not
313 treated using current surgical techniques (Riecks et al., 2009; Fasanella et al., 2010). Hence,
314 breed standards for at least some brachycephalic dogs could be problematic. Our numerical
315 computations demonstrate that the entire skull shape of the brachycephalic dogs studied leads
316 to severe airflow limitation and obstruction in the nasal passageways, larynx, and trachea.

317

318 A limitation of this study is that we used previously reported inspiratory flow rates
319 (Rozanski et al., 1994; Bernaerts et al., 2010) and adapted them to each dog's bodyweight.
320 Nevertheless, different breeds could have different inspiratory flow rates, especially
321 brachycephalic dogs, and discrepancies might exist between computed and real values.
322 Additionally, 3D geometries are considered rigid and therefore do not account for airway
323 compliance. However, because of the relative inflexibility of the nasal cavity (Hostnik et al.,
324 2017), this is not expected to affect our major conclusions. Another study limitation is that
325 CT images were taken in sternal recumbency to maintain a physiological position. The
326 natural standing position could somewhat modify anatomical geometry (Wei et al., 2017), as
327 could sedation, which might relax the musculature around the larynx. Finally, statistical
328 analyses to compare different skull index types was not performed. However, the goal of this
329 work was not to determine statistically significant differences in airflow relationships

330 between skull index types, but rather to demonstrate the feasibility of CFD for the
331 quantification of upper airway resistance in nine dogs of different breeds.

332

333 **Conclusions**

334 CT-based CFD is a non-invasive technique that can demonstrate changes in airway
335 pressure and resistance in different dog breeds. In brachycephalic dogs, we were able to
336 identify numerically different pressure distributions compared with dolichocephalic and
337 mesocephalic dogs, demonstrating differences in the nasal apertures or soft palate. This
338 method could support clinical decision making and surgical planning in cases of obstructive
339 upper airway and tracheal disease. CT-based CFD simulations should be further evaluated as
340 diagnostic tools to improve clinical outcomes and better understand anatomical predisposition
341 the risk of BOAS.

342

343 **Conflict of interest statement**

344 None of the authors has any financial or personal relationships that could
345 inappropriately influence or bias the content of the paper.

346

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354

355 **Appendix: Supplementary material**

356 Supplementary data associated with this article can be found, in the online version, at
357 doi: ...'

358

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516 **Table 1**

517 Skull index (skull width/skull length x 100) and new skull index (Koch et al. 2012) obtained for each dog on multiplanar reconstructed computed
518 tomographic images

	Breed	Weight (kg)	Skull length (cm)	Skull width (cm)	Cerebrum length (cm)	Skull index	New skull index
Dolichocephalic	Great Dane	78.6	26.1	13.2	12.6	51	2.0
	Whippet	10.3	16.3	8.9	8.4	55	1.9
	Dachshund	12.2	16.8	9.0	8.5	54	2.0
Mesocephalic	Belgian shepherd	30.0	21.6	11.0	10.7	51	2.0
	Labrador	29.4	20.8	11.4	10.6	55	2.0
	Brittany spaniel	13.0	16.7	9.9	8.8	59	1.9
Brachycephalic	French bulldog	15.1	12.6	11.8	8.1	93	1.6
	Boxer	39.0	18.2	13.0	11.1	71	1.7
	English bulldog	19.0	14.3	11.1	8.6	77	1.6

519 **Table 2**

520 Flow, pressure difference (Δp) and resistance between the nose and larynx in the upper
521 airways

		Flow (L/min)	Δp (cmH ₂ O)	Resistance (cmH ₂ O/L/min)
Dolichocephalic	Great Dane	88.4250	0.6771	0.0077
	Whippet	11.5875	0.1843	0.0155
	Dachshund	13.7250	0.1892	0.0138
Mesocephalic	Belgian shepherd	33.7500	0.5585	0.0166
	Labrador	33.0750	0.8733	0.0264
	Brittany spaniel	14.6250	0.2240	0.0153
Brachycephalic	French bulldog	12.5571	1.5428	0.1228
	Boxer	32.4324	8.4442	0.2603
	English bulldog	15.8004	1.3012	0.0823

522

523 **Table 3**

524 Flow, pressure difference (Δp) and resistance between the larynx and trachea in the upper
 525 airways.

		Flow (L/min)	Δp (cmH ₂ O)	Resistance (cmH ₂ O/L/min)
Dolichocephalic	Great Dane	80.4174	0.6668	0.0083
	Whippet	22.6249	0.0676	0.0029
	Dachshund	11.1854	0.1892	0.0169
Mesocephalic	Belgian shepherd	28.1240	0.2732	0.0097
	Labrador	29.2017	0.1325	0.0045
	Brittany spaniel	10.2754	0.1071	0.0104
Brachycephalic	French bulldog	10.0294	0.1911	0.0191
	Boxer	12.1020	0.0148	0.0012
	English bulldog	16.2401	21.3551	1.3149

526

527 **Figure legends**

528

529 Fig. 1. CT-based three-dimensional model generation. One dog breed (Great Dane) is shown
530 as an example: the four green markers correspond to transverse sections on CT from the
531 rostral nasal cavity to the laryngeal entrance to the trachea, extracted from images and used
532 with the other sections (not shown) for building the entire model (represented in purple).

533

534 Fig. 2. Reconstructed CT-based geometry in the Great Dane (a), Whippet (b), Dachshund (c),
535 Labrador (d), Belgian shepherd (e) Brittany spaniel (f), Boxer (g), French bulldog (h) and
536 English bulldog (i).

537

538 Fig. 3. Boundary conditions and locations used for the computation (a): Sections 1-4 with
539 their respective computational grids along the canine upper airways and trachea were used for
540 computing flow, pressure decrease and resistance for a Labrador. The results of the mesh
541 independence study are shown in the lower panel (b). The average pressure (cmH₂O)
542 computed on the four sections is plotted as a function of the grid size. The plotted values refer
543 to the atmospheric pressure.

544

545 Fig. 4. Computed flow represented by velocity streamlines for Great Dane (a), Whippet (b),
546 Dachshund (c), Labrador (d), Belgian shepherd (e) Brittany spaniel (f), Boxer (g), French
547 bulldog (h) and English bulldog (i), respectively. Higher velocities are in red (red arrow) and
548 low velocities in blue (blue arrow). Velocity is expressed in m/s.

549

550 Fig. 5. Computed pressure represented by means of coloured surface for Great Dane (a),
551 Whippet (b), Dachshund (c), Labrador (d), Belgian shepherd (e) Brittany spaniel (f), Boxer

552 (g), French bulldog (h) and English bulldog (i). Different colours indicate different pressures
553 (cmH₂O) indicated by arrows. Higher pressures are in red and lower pressures in blue.

554

555 Fig. 6. Ventral view of the distribution of pressure (up, cmH₂O) and velocity streamlines
556 (down, m/s) in the English bulldog with the corresponding CT section, highlighting tracheal
557 stenosis (red arrow).

558

559 Fig. 7. Ventral view of the spatial distribution of pressure (up, cmH₂O) and velocity (down,
560 m/s) in the Boxer, with the corresponding CT sections highlighting the asymmetric nasal
561 cavity (red circle). Regions coloured in yellow, red, green and blue are characterized by
562 different pressure and velocity values.

563

564 Fig. 8. Computed pressure reductions (cmH₂O) between the nose and larynx (a) and between
565 larynx and trachea (b) with a close-up view on each single breed; dolichocephalic (a.1 and
566 b.1), mesocephalic (a.2 and b.2), and brachycephalic (a.3 and b.3).

567

568 Fig. 9. Computed resistance (cmH₂O/L/min) between the nose and larynx (a) and between the
569 larynx and trachea (b) with a close-up view on each dog; dolichocephalic (a.1 and b.1),
570 mesocephalic (a.2 and b.2), and brachycephalic (a.3 and b.3) skull types.

